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Abstract: A lake-level record for the late Holocene at Lake Ledro (Trentino, northeastern Italy) is presented. It is based on the sediment and pollen analysis of a 1.75 m high stratigraphic section observed on the southern shore (site Ledro I) and a 3.2 m long sediment core taken from a littoral mire on the southeastern shore (site Ledro II). The chronology is derived from 15 radiocarbon dates and pollen stratigraphy. The late-Holocene composite record established from these two sediment sequences gives evidence of centennial-scale fluctuations with highstands at *c*. 3400, 2600, 1700, 1200 and 400 cal. BP, in agreement with various palaeohydrological records established in central and northern Italy, as well as north of the Alps. In addition, high lake-level conditions at *c*. 2000 cal. BP may be the equivalent of stronger river discharge observed at the same time in Central Italy's rivers. In agreement with the lake-level record of Accesa (Tuscany), the Ledro record also suggests a relatively complex palaeohydrological pattern for the period around 4000 cal. BP. On a millennial scale, sediment hiatuses observed in the lower part of the Ledro I sediment sequence indicate that, except for a highstand occurring just after 7500 cal. BP, lower lake levels generally prevailed rather before *c*. 4000 cal. BP than afterwards. Finally, the lake-level data obtained at Lake Ledro indicate that the relative continuity of settlements in humid areas of northern Italy during the Bronze Age (in contrast to their general abandonment north of the Alps between *c*. 3450 and 3150 cal. BP), does not reflect different regional patterns of climatic and palaeohydrological conditions. In contrast, the rise in lake level dated to *c*. 3400 cal. BP at Ledro appears to coincide with a worldwide climate reversal, observed in both the hemispheres, while palaeoenvironmental and archaeological data collected at Lake Ledro may suggest, as a working hypothesis, a relative emancipation of protohistoric societies from climatic conditions.

Key words: Lake level, late Holocene, northern Italy, sedimentology, Bronze Age lake-dwellings.

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Introduction

On the basis of *c.* 150 tree-ring dates, which establish a robust chronological framework of Neolithic and Bronze Age lake-dwellings in west-central Europe, previous studies have shown that the frequency of prehistoric lake-shore villages can be compared with the residual atmospheric ^{14}C record (Magny, 1993). The peaks in frequency correspond to ^{14}C minima (stronger solar activity). In addition to lake-level studies from multiple sediment sequences from lakes north of the Alps, this correlation suggests that higher solar activity induced warmer climate and lake-level lowering, which in turn favoured the expansion of lake-dwellings (Magny, 2004). More particularly, the two tree-ring defined periods 3751–3460 cal. BP (Early Bronze Age and first part of the Middle Bronze Age) and 3070–2764 cal. BP (second part of the Final Bronze Age) corresponded to both a large development of lake-shore villages associated with warmer and drier climate conditions, while after *c.* 3450 cal. BP, most of the Middle Bronze Age coincided with a general abandonment of lake-dwellings consecutive to a rise in regional lake levels and wetter climate conditions (Magny, 1993, 2004; Zolitschka *et al*., 2003; Sadori *et al*., 2004; Magny *et al*., 2009).

The history of prehistoric settlements in wet areas such as those recognized north of the Alps strongly contrasts with that reconstructed south of the Alpine Mountains. In northern Italy, archaeologists observed not only that a relative continuity of lake-dwellings maintained all through the Bronze Age, but also that the Middle Bronze Age (3600–3300 cal. BP) seems to mark a maximal development of lake-shore and wetland pile-dwelling villages (Perini, 1994; Guidi and Bellintani, 1996; Martinelli, 2005; Magny and Peyron, 2008). The regional peculiarity of northern Italy is still confirmed by the so-called Terramare, ie, fortified villages which developed in humid areas of the Po plain during the Middle and Recent Bronze Age between 3550 and 3100 cal. BP (Cremaschi *et al*., 2006).

Unfortunately, palaeohydrological records established from high-resolution studies of lacustrine sediment sequences and based on robust chronological data are still rare in northern Italy, to test whether the differences observed between the history of Bronze Age lake-dwellings north and south of the Alps were linked to different regional palaeohydrological patterns or to a different socio-economic organization of societies. As a contribution to such a test, this paper presents a lake-level record established for the last 4500 years at Lake Ledro (Figure 1), which is a site famous for remains of Early and Middle Bronze Age lake-dwellings (Battaglia, 1943; Rageth, 1974; Leonardi *et al*., 1979; Cortesi and Leonardi, 2002). A further and more specific study based on pollen and plant macrofossils will deal with the vegetation dynamics in relation with climate and human impact.

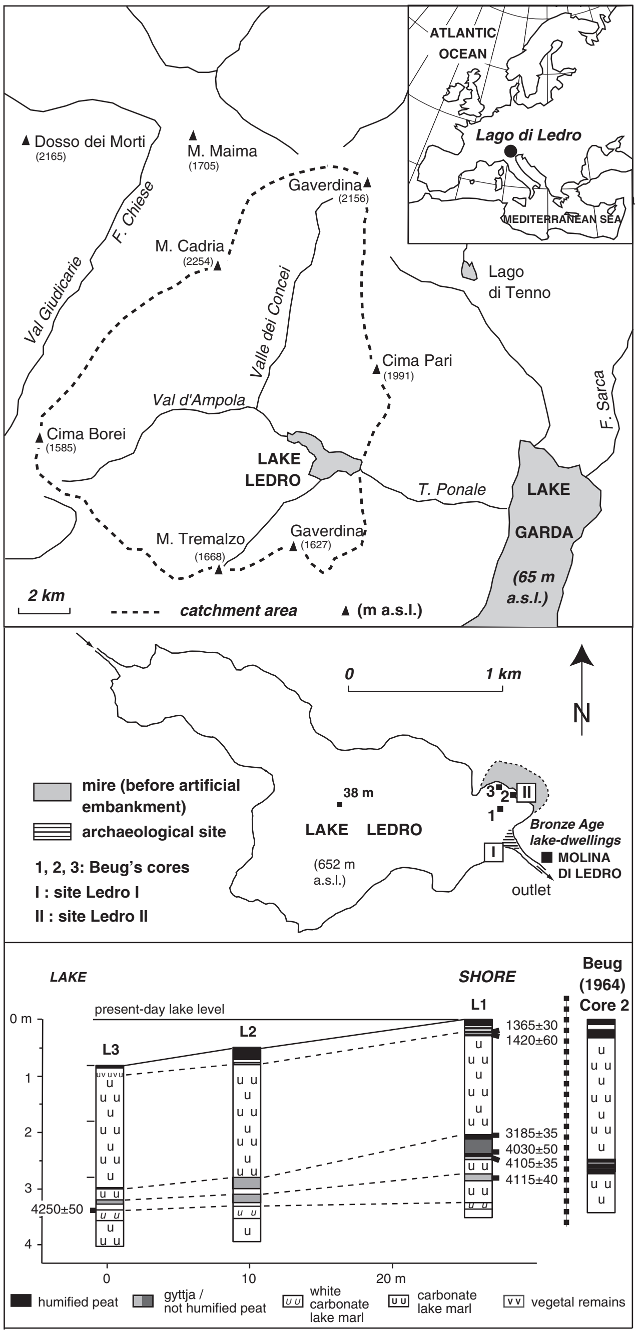

Figure 1 Upper panel: location and catchment area of Lake Ledro in northern Italy. Middle panel: location of sites Ledro I and II (present study), and of coring sites of Beug (1964). Lower panel: core transect established on the site of Ledro II. On the right the lithostratigraphic profile of core 2 pollen analysed by Beug (1964) is shown

Site and methods

Lake Ledro (45°87′N, 10°76′E; Italian: Lago di Ledro) is located at 652 m a.s.l. on the southern slope of the Alps, at *c.* 6 km in the north of Lake Garda (Figure 1). It is a relatively small lake (2.8 km long, 0.8 km wide), its present water depth reaching 38 m. The surrounding mountains culminate at *c.* 1500–2200 m a.s.l. The lake surface is *c.* 2.17 km^2 and the catchment area covers *c.* 131 km^2 and is characterized by relatively steep slopes. The substratum is mainly composed of Triassic (dolomite), Jurassic and Cretaceous limestone. The outlet of Lake Ledro is the Ponale River, which is responsible for downcutting in a morainic dam (Beug, 1964). Since 1929, the water-table has been artificially regulated for hydroelectricity.

Owing to the influence of a large body of water, the region of Lake Garda (65 m a.s.l.) is famous for particularly mild climatic conditions, which allow the presence of Mediterranean species. Around Lake Garda, olive groves reach 300 m a.s.l. and isolated olive trees even 600 m a.s.l. The shores of Lake Garda were also well-known for plantations of lemon trees protected against possible winter frost. *Quercus ilex* is present in the Sarca valley as well as *Erica arborea* in the Chiese valley (Figure 1; Beug, 1964). However, because of higher altitude, the vegetation in the Ledro valley is dominated by *Fagus* mixed with *Abies*, then *Picea* in the higher part of the montane belt (650–1600 m), and by *Pinus mugo, Alnus viridis, Larix* and *Picea* in the subalpine belt (1600–2000 m). Above 2000 m a.s.l. grasslands dominate (Beug, 1964). Generally

Table 1 AMS radiocarbon dates obtained on terrestrial plant macroremains and from littoral peat at sites Ledro I and II

Core	Depth (cm)	Radiocarbon date	Calibrated age (1 sigma)	Calibrated age (2 sigmas)	Laboratory reference	Material
Ledro I	47–48	1490 ± 35	1405–1342 cal. BP	1509–1304 cal. BP	Poz-11068	charcoal + bark
	77–88	1870 ± 30	1868–1740 cal. BP	1877–1724 cal. BP	Poz-11069	wood fragments
	97–98	2195 ± 30	2306–2151 cal. BP	2317–2131 cal. BP	Poz-11070	wood fragments
	119–120	2250 ± 140	2451–2009 cal. BP	2707–1934 cal. BP	Poz-13143	charcoal
	125–126	3245 ± 35	3553–3404 cal. BP	3559–3392 cal. BP	Poz-11893	charcoal + bark
	140–142	3280 ± 35	3558–3467 cal. BP	3610–3406 cal. BP	Poz-11894	charcoal
	152–153	3695 ± 35	4085–3985 cal. BP	4149–3927 cal. BP	Poz-11072	charcoal
	172–173	6900 ± 130	7914–7619 cal. BP	7972–7514 cal. BP	Poz-13144	charcoal
Ledro II						
L1	21–22	1365 ± 35 BP	1309–1279 cal. BP	1339–1189 cal. BP	Poz-17035	peat
	23–24	1420 ± 60 BP	1369–1290 cal. BP	1507–1184 cal. BP	Poz-18588	peat
	204–205	3185 ± 35	3444–3381 cal. BP	3470–3356 cal. BP	Poz-17036	twigs
	236–237	4030 ± 50	4569–4425 cal. BP	4805–4413 cal. BP	Poz-18596	peat
	244–245	4105 ± 35	4799–4530 cal. BP	4816–4453 cal. BP	Poz-17038	peat
	280–281	4115 ± 40	4807–4535 cal. BP	4822–4524 cal. BP	Poz-17039	twigs
L3	70–71	4250 ± 50	4865–4662 cal. BP	4960–4590 cal. BP	Poz-21190	wood fragments

speaking, in the Ledro valley, mixed oak forest does not develop; lime trees are rare, while elm and maple trees may be present in *Fagus* forests. At Molina di Ledro, the mean temperature is *c.* 0°C in the coldest month (January) and *c.* 20°C in the warmest month (July). The annual precipitation ranges from *c.* 750 to *c.* 1000 mm, with seasonal maxima in spring and autumn.

Two sites, ie, Ledro I and Ledro II, have been chosen for lake-level studies (Figure 1). Ledro I is located on the southeastern shore, just west of a place occupied by Middle Bronze Age lake-dwellings in the outlet area. Littoral erosion due to natural factors in combination with large annual fluctuations of water level for hydroelectricity offered the opportunity in April 2005 to observe and sample a 1.75 m high stratigraphic section above the lowered water level. Overlying morainic deposits and a pebble beach formation, the sediment sequence observed along a *c.* 100 m section highlights an alternation of different layers composed of carbonate lake marl, oncolites and peaty sediments. In addition, the geometry of the sediment layers gives evidence of erosion surfaces (see below). Site Ledro II is located on the northeastern shore, in a small littoral mire which is the residual part of a large peat area artificially embanked for the installation of a camping site. There, by means of a Russian peat corer, a 30 m long core transect perpendicular to the shore, has been carried out to recognize the sediment stratigraphy. Figure 1 (lower panel) shows the upper part of the sequence which is of interest for this study. Considered as a whole, under the superficial peat layer, the sediment sequence shows an accumulation of carbonate lake-marl interrupted by deposition of organic layers (peat, gyttja) which are better developed towards the lake shore. Core L1 was chosen for sediment analysis because it offered the most complete contrasting lithostratigraphical profile with the best development of organic layers. Ledro II is close to coring sites pollen-analysed by Beug (1964) for the Lateglacial and Holocene vegetation history (Figure 1).

Pollen preparation followed standard methods using treatment with HCL, 10% KOH, HF, acetolysis and final mounting in glycerine. More than 450 terrestrial pollen grains were counted for each sample. Cyperaceae, palustrine taxa, aquatics and spores are systematically excluded from the pollen sum. All pollen types are defined according to Faegri and Iversen (1989), although some identifications require the use of a pollen atlas (Reille, 1992–1998). At Ledro I, the pollen grains were not preserved in the lower part of the sediment sequence below 97 cm (except for one sample at 120 cm), while at Ledro II the pollen preservation, although not always excellent, was good enough to establish a complete pollen diagram. Beyond causes linked to lake-level fluctuations (see below), the differences in pollen preservation between Ledro I and II probably originate from different geomorphologic conditions: site Ledro II is located on the fringe of a large littoral mire favourable to retaining underground water, while site Ledro I is characterized by a narrow littoral zone close to relatively steep slopes of the catchment area.

The lake-level fluctuations were reconstructed using a sedimentological method (Magny, 1998, 2006), based on multiple lines of evidence, including changes in lithology and relative frequency of various carbonate concretion morphotypes of biochemical origin. Modern analogue studies demonstrated that each morphotype shows a specific spatial distribution from the shore to the extremity of the littoral platform, with the successive domination of oncolites (nearshore areas with shallow water and high energy environment), cauliflower-like forms (littoral platform), plate-like concretions (encrustations of leaves from the Potamogetonion and Nymphaeion belts) and finally tube-like concretions (stem encrustations from the Characeae belt on the platform slope). In addition to variations in the assemblages of carbonate concretions, the relative frequency of plant macroremains and mollusc shells provide further information about the deposition environment. The abundance of mollusc shells increases towards the shore (Mouthon, 1984) as do vegetal remains partly inherited from littoral vegetation (particularly lignosous vegetal remains). Moreover, erosion surfaces (sediment hiatuses) evidenced by uncoformities between sediment layers (Mitchum *et al*., 1977; Digerfeldt, 1988) point to a lowering of the sediment limit associated with a lowering of the lake level.

The chronology is based on 15 AMS radiocarbon dates (Table 1) from terrestrial plant macroremains or from littoral peat deposits. The ages have been calculated using IntCalib 5 (Stuiver *et al*., 1998). Additional chronological indications are provided by the regional pollen stratigraphy (Figures 2 and 3).

Results

Vegetation and human-impact history

The results of pollen analysis are presented in Figure 2. The present study focuses on the general pollen stratigraphy established on the basis of the Ledro II record which provided a complete pollen diagram. One may observe that the main features of the vegetation history reconstructed at Ledro for the late Holocene appear to be

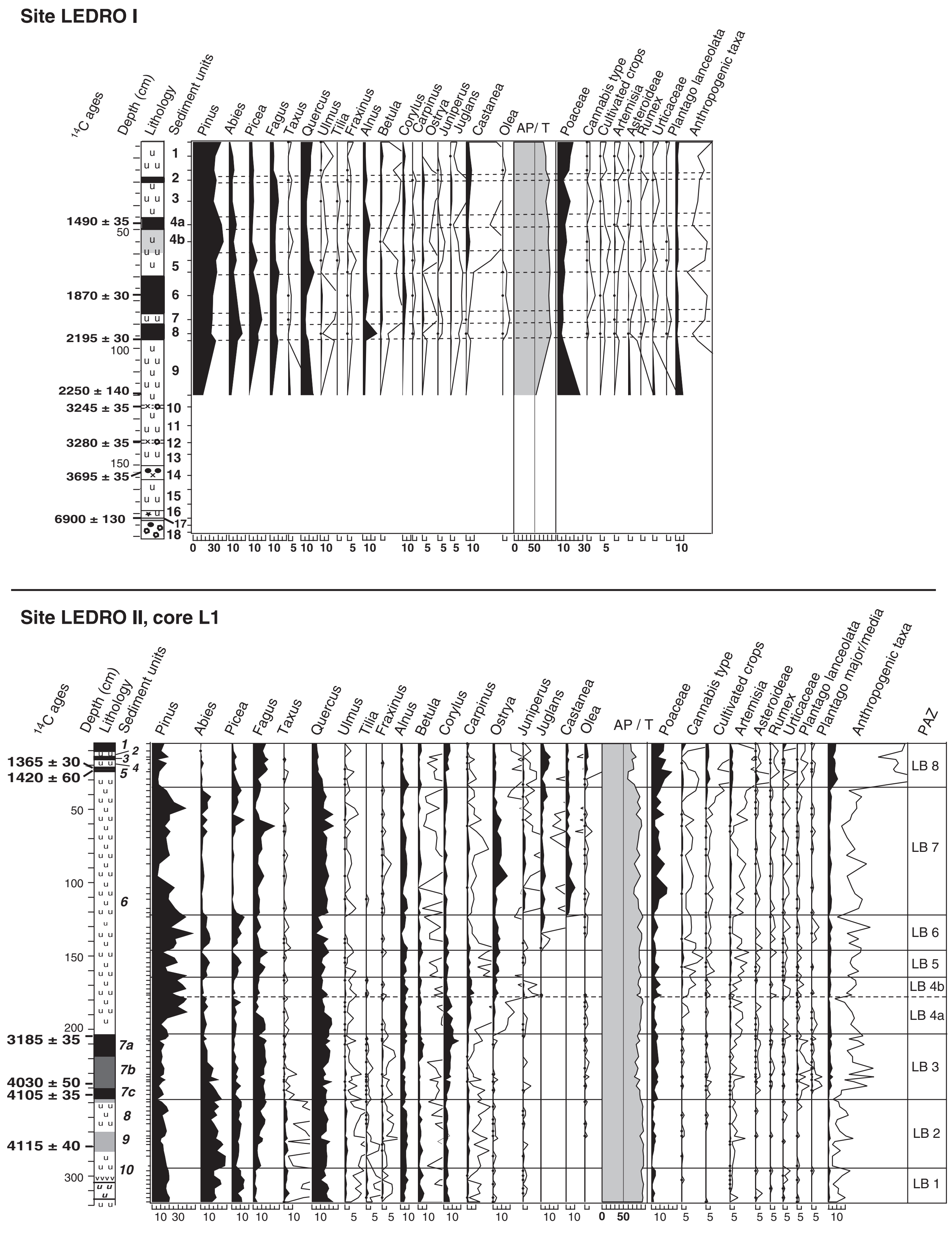

Figure 2 Simplified pollen diagrams of sites Ledro I (upper panel) and II (lower panel). Cultivated crops: *Cerealia*-type, *Triticum*-type, *Secale*; anthropogenic taxa: *Plantago major/media*-type, *Plantago lanceolata*, *Plantago* sp., *Artemisia*, *Urtica*, *Echium*-type, *Rumex* sp., *Rumex acetosa/acetosela*-type, Brassicaceae, Rubiaceae, Chenopodiaceae, Asteroideae, Cichoriodeae, *Centaurea cyanus*, Papaveraceae. Exaggerated curves are × 10. In the Ledro I sequence, pollen grains were not preserved below level 120 cm. PAZ, pollen assemblage zones

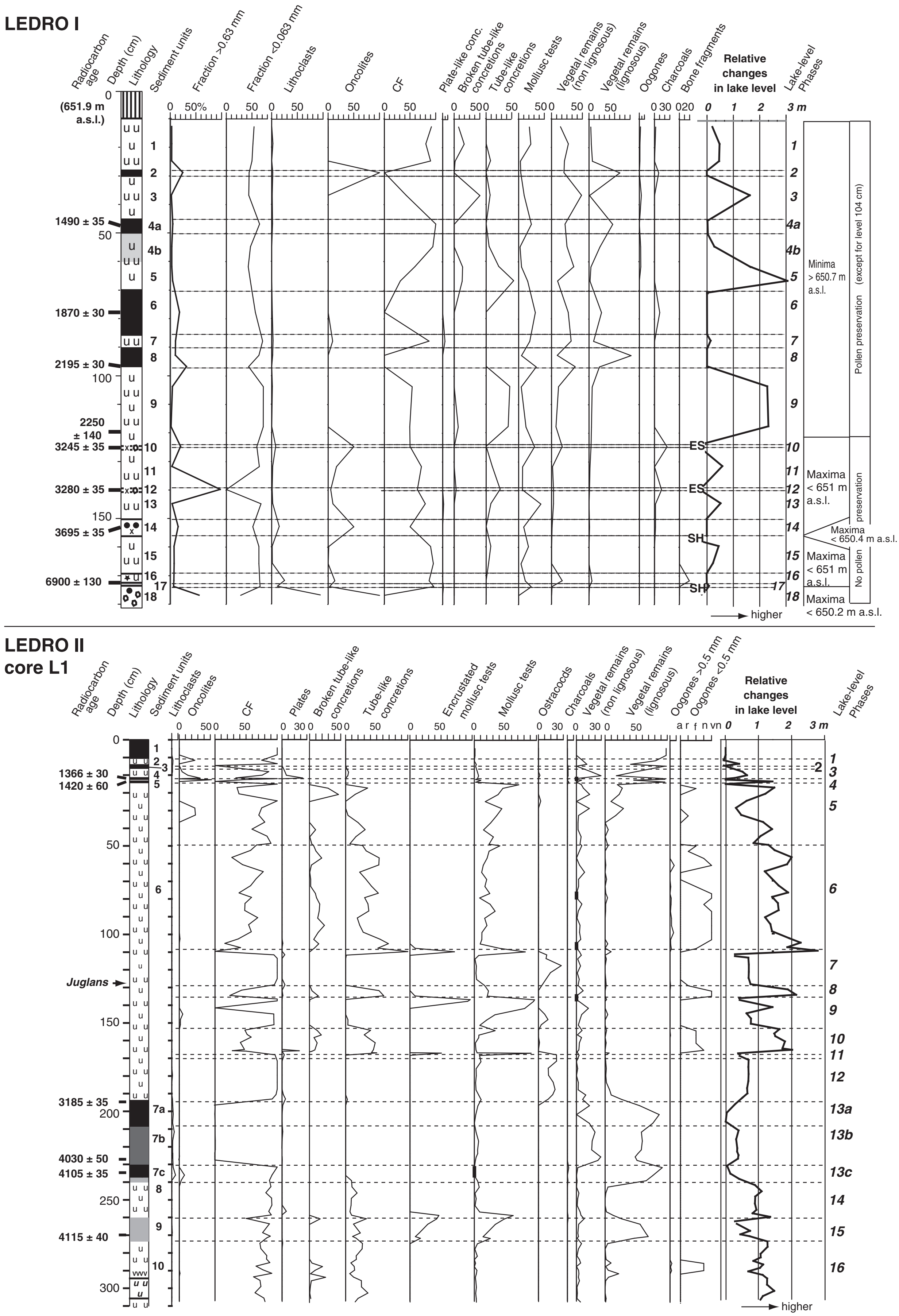

Figure 3 Upper panel: sedimentological diagram and lake-level fluctuations established from site Ledro I. Lower panel: sedimentological diagram and lake-level fluctuations established from site Ledro II. The arrow indicates the development of *Juglans* as observed by pollen stratigraphy (see Figure 2). ES, erosion surface; SH, sediment hiatus; CF, cauliflower-like concretions. Oogones (fraction < 0.063 mm): a, absent; r, rare; f, frequent; n, numerous; vn, very numerous (ie, more than 40/cm^3)

consistent with the pollen stratigraphy previously recognized by Beug (1964). The lower part of the sequence (LB1 and LB2 pollen assemblage zones) is characterized by a stronger development of a coniferous forest dominated by *Pinus* (*P. sylvestris* type), *Abies* and to a lesser extent *Picea,* while *Taxus* shows a nearly continuous representation with percentages of *c.* 5% (less than in Beug's diagrams). A mixed oak forest with *Ulmus*, *Tilia* and *Fraxinus* is also well represented. During pollen assemblage zone LB2 the values of *Fagus* increase to reach *c.* 15%, and *Abies* surpasses *Pinus*. From pollen zone LB3, the history of the forest appears to have been characterized by (1) a decrease of the fir-spruce forest punctuated by short intermediate phases of increase (zones LB5, LB6, and upper part of LB7), (2) the quasi-disappearance of *Taxus*, *Tilia* and *Fraxinus* as well as the strong retreat of *Ulmus* which is only represented by irregular and low values, (3) the expansion of *Pinus* during pollen zones LB4a and LB4b, with values reaching 30%, (4) the development and the continuous curve of *Ostrya* from zone LB4a, and finally (5) the successive development of *Juglans* (zone LB6) and *Castanea* (zone LB7), while *Olea* shows an increase during zone LB8. A pollen record recently established at Lago Lavarone in Trentino (Filippi *et al*., 2007a) gives evidence of similar features, with successive appearances of *Juglans* and *Castanea*, respectively dated to 2110 ± 80 BP (ie, 2310–1920 cal. BP) and *c.* 1800 BP, ie, 1820–1690 cal. BP (extrapolated age). When taking into account uncertainties inherent in radiocarbon ages, this is consistent with the pollen data obtained from Ledro I sequence where levels 97 and 68 cm are characterized by the successive developments of *Juglans* and *Castanea* and have been dated to 2317–2131 cal. BP (2195 ± 30 BP) and after 1877–1724 cal. BP (1870 ± 30 BP), respectively.

Regarding human-impact history, scarce occurrences of cereal and anthropogenic indicators may show, during pollen zones LB1 and LB2, a low or moderate human pressure near the shores of Lake Ledro. Zone LB3 reflects a strong increase in human activity during the Bronze Age. This is characterized by high values of anthropogenic indicators (cultivated crops and anthropogenic taxa) and by important clearance of forest as shown by a synchronic reduction of forest taxa such as *Abies*, *Picea*, *Taxus* and *Ulmus*. In zone LB4a, the quasi-disappearance of the cereal pollen-type, and the decrease in anthropogenic taxa (*Urtica, Plantago lanceolata, Rumex*) may reflect a short period of reduction in agro-pastoral activities, immediately followed by a new increase of human pressure in zone LB4b. As indicated by pollen data, human activities such as cultivation (probably including *Cannabis* cultivation; Mercuri *et al*., 2002) and grazing remain stable and regular until the top of the record. The increase in Poaceae and the strong reduction of the fir-spruce forest recorded during zone LB7 reflect the development of open areas during the Roman period, probably linked to an intensification of forest clearances. However, the Medieval period seems to be most important for human activities in the Ledro region. All anthropogenic indicators show a strong increase correlated to a reduction of forest cover.

Lake-level fluctuations

Figure 3 shows sediment diagrams established from Ledro I and II sediment sequences. On the right, curves of relative changes in lake level indicate the ratio between the total scores of markers of low lake-level conditions (ie, oncolites and cauliflower-type concretions, encrusted mollusc tests, lignosous vegetal remains), and those of high lake-level conditions (ie, plate and tube concretions, oogones of Characeae; Magny, 1998, 2006).

The Ledro I sediment sequence appears to have been affected by several hiatuses and erosion surfaces because of (1) relatively high elevation a.s.l., and (2) the general Holocene history of the lake level. The curve of relative changes in lake level shows 18 distinct successive phases of high and low water-table as follows (Figure 3).

On top of the basal morainic deposits a pebble beach layer is observed characteristic for lake-shore sedimentation. This phase (18) developed before 6900 ± 130 BP (ie, 7972–7514 cal. BP). A slight rise in lake level (phase 17) provoked the sedimentation of a first thin carbonate lake-marl layer, which overlies the morainic deposits. Afterwards, the Ledro I sediment sequence gives evidence of eight successive phases of low lake level marked by peaks of oncolites, lithoclasts (terrestrial input) and coarser texture (phases 16, 14, 12 and 10), or by the formation of peat layers (phases 8, 6, 4 and 2). Unconformities between sediment layers highlight the development of erosion surfaces during phases 12 and 10, while radiocarbon ages point to sediment hiatuses before 3695 ± 35 (ie, 4149–3927 cal. BP) and 2250 ± 140 BP (ie, 2707–1934 cal. BP). Unfortunately, sediment unit 2 (peat) provided an inconsistent radiocarbon age probably because of reworked material. An extrapolated age of *c.* 750 cal. BP can be assumed for sediment unit 2. Intermediate phases 17, 15, 13, 11, 9, 7, 5, 3 and 1 correspond to higher lake-level conditions marked by accumulation of carbonate lake-marl with a finer texture, the development of plate and tube concretions and a decline of oncolites. Phases 9 and 5 point to major rises in the water-table as indicated by peaks of tube concretions (Figure 3).

Regarding the chronology of the sediment diagram established from the sediment sequence Ledro II, no sufficient and appropriate organic material has been found to obtain radiocarbon dates from sediment unit 6. On the other hand, it seems difficult to extrapolate ages assuming a regular sedimentation rate because several abrupt jumps in the representation of encrusted mollusc tests (characteristic for lake-shore sedimentation) and tube concretions (indicators of maximums in lake level) point to possible short sedimentation hiatuses at levels 178, 146 and 118 cm. Such a jump also appears at level 270 cm. However, the pollen stratigraphy, with the successive development of *Juglans* and *Castanea* at levels 138 and 120 cm, respectively, provides additional chronological references (see above).

The curve of relative changes in lake level shows 16 distinct successive phases as follows (Figure 3). During phase 16 which occurred before 4115 ± 40 BP (ie, 4822–4524 cal. BP), generally high lake-level conditions prevailed (development of tube concretions). Stratigraphic correlation between cores L1, L2 and L3 (Figure 1) allows dating of phase 16 to *c.* 4250 ± 50 BP (ie, 4960–4590 cal. BP). Phase 15 coincides with a lowering marked by the deposition of gyttja (sediment unit 9) and a peak in encrusted mollusc tests. Between 4115 ± 40 and 4105 ± 35 BP (ie, between 4822–4524 and 4816–4453 cal. BP), phase 14 corresponds to higher lake-level conditions provoking the cessation of gyttja deposition and the disappearance of encrusted mollusc tests. From *c.* 4105 ± 35 BP to 3185 ± 35 BP (ie, from 4816–4453 to 3470–3356 cal. BP), phase 13 is characterized by prevailing low lake-level conditions, which favoured the deposition of organic layers. However, in sediment unit 7, the interbedding of a layer composed of not humified brown peat between two humified black peat layers suggests that phase 13 was interrupted by a slight rise event. As illustrated by Figure 1, the profile of core 2 studied by Beug (1964) shows a more complex picture for sediment unit 7 with two gyttja layers interbedded between three peat layers.

After 3185 ± 35 BP (ie, 3470–3356 cal. BP), the return to carbonate lake-marl sedimentation points to a new rise in lake level (phase 12) which later reached successive maxima (phases 10, 8 and 6) well marked by peaks in tube concretions and oogones of Characeae. Peaks of encrusted mollusc tests give evidence of pronounced intermediate lowering episodes (phases 11, 9 and 7). Two successive peaks in oogones of Characeae suggest that phase 6 is composed of two distinct events. Generally speaking, phase 5 marks a trend towards lower lake-level conditions (development of mollusc tests, oncolites, cauliflower concretions, strong decline in oogones). In the upper part of the sediment sequence, the alternation of carbonate and peat layers reflects the succession of highstands (phases 3 and 1) and lowstands, ie, phase 4 composed of two successive events dated to 1420 ± 60 (ie, 1507–1184 cal. BP) and 1365 ± 30 BP (ie, 1339–1189 cal. BP) and phase 2. Recent archaeological excavations allow more precise dating of phase 4 to *c.* 1380–1330 cal. BP on the basis of archaeological artefacts found in sediment unit 5 (Dal Ri and Piva, 1987). Hence, an extrapolated age of *c.* 1000 cal. BP can be assumed for phase 2.

Taking into account radiocarbon dates in addition to the pollen stratigraphy and the palaeohydrological signal (highstands versus lowstands), the comparison of the two lake-level records Ledro I and Ledro II make it possible to establish (1) correlations between centennial-scale events recognized from both sites, and (2) a synthetic lake-level record for Lake Ledro as illustrated by Figure 4. The main difficulties for these correlations arise from sediment unit 6 of sequence Ledro II which did not provide any radiocarbon dates. However, the pollen stratigraphy suggests that phase 7 of Ledro II (characterized by the beginning of the development of *Juglans* at level 138 cm, and absence of *Castanea* until level 120 cm) may be an equivalent to phases 6, 7 and 8 of Ledro I (marked by the development of *Juglans* while *Castanea* is still poorly represented). Hence, phase 6 of Ledro II appears to be an equivalent to phase 5 of Ledro I, characterized by a more pronounced development of *Castanea* just after 1870 ± 30 BP, ie, 1877–1724 cal. BP (Figure 2). Subsequently, phase 8 of Ledro II may be an equivalent to phase 9 of Ledro I. Owing to the lack of radiocarbon dates in sediment unit 6 of Ledro II, in addition to the absence of preservation of pollen grains below level 120 cm and the sediment hiatus between sediment units 10 and 9 at Ledro I, it remains impossible to firmly indicate any equivalent to phases 10 and 11 of Ledro II in the sequence Ledro I. However, the chronological proximity of phases 12 and 10 of Ledro I suggests that the period of higher lake-level conditions following phase 13a at Ledro II composed of distinct successive highstand phases. Hence, phase 10 of Ledro I may be correlated with phase 11 of Ledro II.

In addition to a series of centennial-scale palaeohydrological events illustrated by Figure 4, the sediment sequence Ledro I suggests millennial-scale variations over the late Holocene (Figure 3, upper panel). First of all, it is remarkable that no sediment deposition occurred on the site of Ledro I during the first part of the Holocene. The first significant accumulation of lacustrine sediment, ie, the 15 cm thick sediment unit 15, developed just after 6900 ± 130 BP (ie, after *c.* 7500 cal. BP), as suggested by the preservation of the thin sediment units 17 and 16. But, the composition of sediment unit 15 indicates that lake-level maxima did not go beyond 651 m a.s.l. Afterwards, the sediment hiatus observed between sediment units 15 and 14 reflects a period of low lake-level conditions (before 4000 cal. BP) with maxima of the water-table less than 650.4 m a.s.l. (no sediment deposition). Thereafter, the sediment sequence of Ledro I shows two successive periods. The first, corresponding to the deposition of sediment units 14 to 10, is characterized by erosion surfaces and/or sediment hiatuses as well as by no preservation of pollen grains. In contrast, the second period from sediment units 9 to 1 shows a better preservation of pollen grains (sufficient to establish a diagram, except for level 104 cm), and gives evidence of a relatively continuous sedimentation. Alltogether, these observations suggest three distinct successive periods as follows (Figure 3).

- Before 6900 ± 130 BP (ie, 7972–7514 cal. BP), the water level is lower than the top of the basal moraine (unit 18), ie, below 650.2 m a.s.l.
- In the second period, a rise in lake level led to the deposition of sediment above 650.15 m a.s.l. during pronounced highstands, while lowstands provoked the cessation of deposition and the formation of sediment hiatuses and erosion surfaces (sediment units 14, 12 and 10). It is noteworthy that between *c.* 7000 and 4000 cal. BP even maximal lake levels remained below 650.4 m a.s.l. (no sediment deposition).
- Finally, during the recent third period, since *c.* 2250 ± 140 BP (ie, 2707–1934 cal. BP), the lake level reached a higher point and sedimentation became relatively continuous above 650.7 m a.s.l., even during the lowstands which coincided with peat accumulation (sediments units 8, 6, 4 and 2).

Discussion and conclusions

Keeping in mind the radiocarbon-age uncertainties, Figure 5 presents a comparison between the centennial-scale fluctuations of lake level reconstructed at Ledro for the last 4500 years and (1) the regional pattern of lake-level changes established for west-central Europe north of the Alps (Magny, 2004, 2006), as well as (2) various palaeohydrological records from central Italy, ie, Lake Fucino (Abruzzo; Giraudi, 1998), Lake Mezzano (Lazio; Giraudi, 2004; Sadori *et al*., 2004), Lake Accesa (Tuscany; Magny *et al*., 2007a) and the Ombrone River delta (southern Tuscany; Bellotti *et al*., 2004), and Calderone glacier in the Gran Sasso Massif (central Apennines; Giraudi, 2005a, b). Taking into account the difficulties linked to the fact that records have been established from different methods and differ in the precision of their temporal resolution and chronology, Figure 5 shows that, within the age uncertainties inherent in radiocarbon dating, lake-level records from Ledro, Fucino, Mezzano and Accesa give evidence of similarities with highstands at *c.* 3400, 2700, 1200 and 400 cal. BP. Lake Ledro also displays a well-marked highstand episode which developed after 2195 ± 30 BP (ie, 2317–2131 cal. BP) and before 1870 ± 30 BP (ie, 1877–1724 cal. BP), and may be synchronous with the one observed at Lake Fucino (Giraudi, 1998) at *c.* 2000 cal. BP as well as with marked floods at the same time in valleys of the rivers Tiber in Roma (Camuflo and Enzi, 1994; Giraudi, 2005b) and Arno in Pisa (Benvenuti *et al*., 2006) in Italy, and in the Rhone delta in France (Arnaud-Fassetta, 2002).

Regarding the period around 4000 cal. BP, the sequences Ledro I and II provide contrasting data. While a lake-level lowering dated to 3695 ± 35 BP (ie, 4150–3930 cal. BP) is observed at Ledro I, the sequence of Ledro II shows a slight rise in lake level which occurred between 4030 ± 50 BP (ie, 4805–4413 cal. BP) and 3185 ± 35 BP (ie, 3470–3356 cal. BP). Moreover, the profile of Beug's core 2 highlights a more complex lithostratigraphy for sediment unit 7, with two gyttja layers interbedded between three peat layers (Figure 1, lower panel) and suggest two successive slight rises in lake level. These contrasting data may reflect differences of elevation between the two sites, but they may also point to a more complex picture of the *c.* 4000 cal. BP cooling event (Marchant and Hooghiemstra, 2004) in the northern Mediterranean area than was previously thought. A multiproxy record from Buca della Renella, a cave in the Alpi Apuane (central-western Italy), has shown a severe drought dated to *c.* 4100 cal. BP synchronous with an IRD event in the North Atlantic Ocean (Bond et al., 2001; Drysdale *et al*., 2006). However, Piva *et al*. (2008) found evidence of a wetter and cooler event at *c.* 4000–3800 cal. BP from marine cores in the Adriatic Sea. In addition, as illustrated by Figure 5, the Accesa lake-level record in central Italy shows two marked low lake-level episodes at *c.* 4100–3900 cal. BP bracketed between two highstands dated to 4250–4100 and 3900–3750 cal. BP (Magny *et al*., 2007a). This appears to be in agreement with the picture given for the same time window by the Ledro lake-level record.

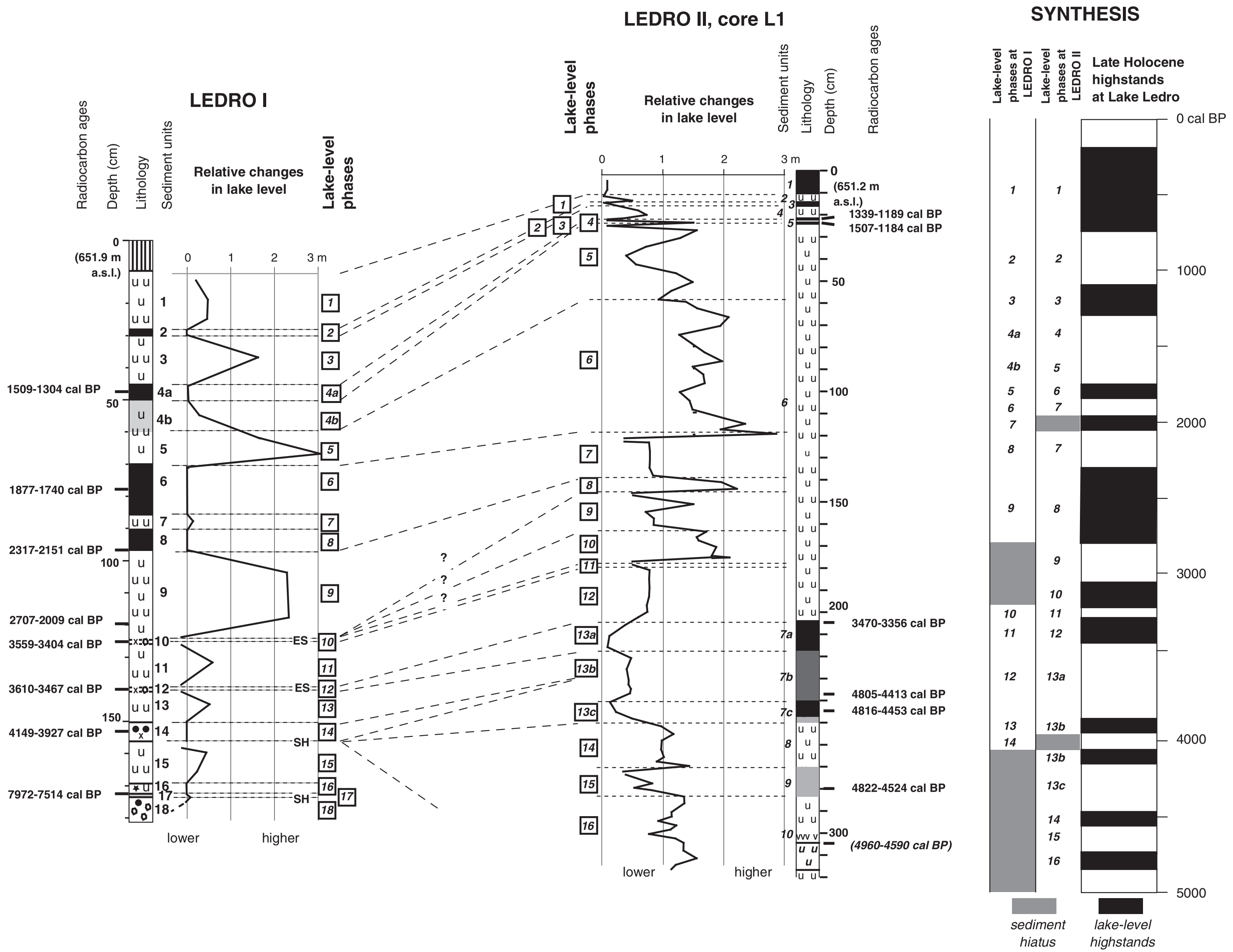

Figure 4 Correlation between lake-level records established from sites Ledro I and II, and synthetic lake-level record for Lake Ledro during the late Holocene. In the synthesis column, the phases of high lake level are marked by black rectangles. Calibrated ages correspond to radiocarbon dates obtained from Ledro I and II sequences (see Figure 3 and Table 1) and from core L3 for the radiocarbon date 4250 ± 50 BP (site Ledro II, see Figure 1)

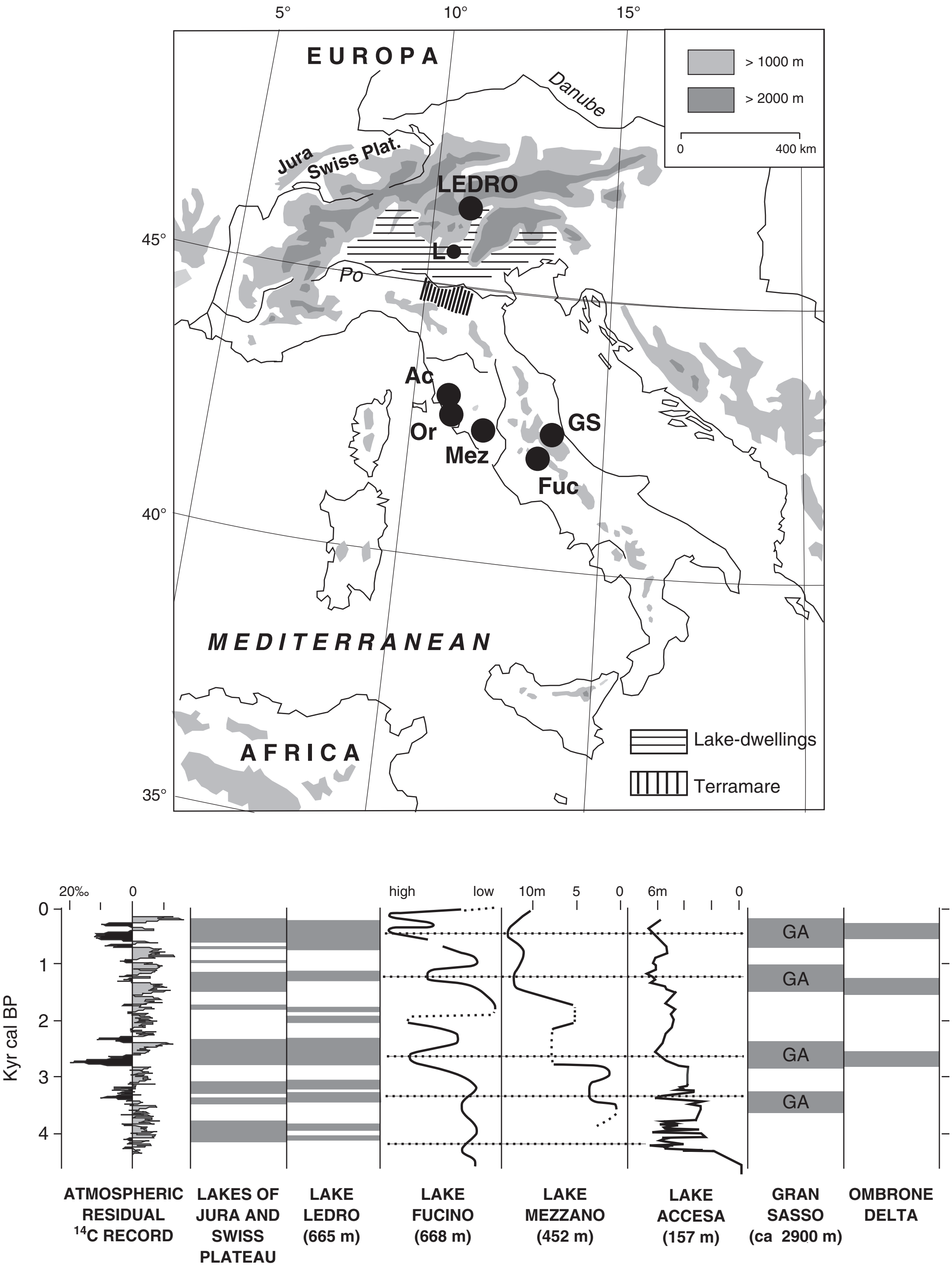

Figure 5 Comparison of the late-Holocene Ledro lake-level record (this study, see Figure 4) with (1) palaeohydrological data obtained in Italy at Fucino (Giraudi, 1998), Mezzano (Giraudi, 2004), Accesa (Magny *et al.*, 2007a), and Ombrone river delta (Bellotti *et al.*, 2004), and in west-central Europe north of the Alps (Magny, 2004, 2006), (2) cooling events on the higher Apennine massifs (Giraudi, 2005a, b), and (3) the atmospheric residual ^{14}C record (Stuiver *et al.*, 1998). GA, glacier advance. Map in the upper panel: Ac, Lake Accesa; Fuc, Lake Fucino; GS, Gran Sasso; L, Lake Lucone; Mez, Lake Mezzano; Or, Ombrone river delta

Considered as a whole, the correlations observed in Figure 5 on a centennial-scale (1) between various palaeohydrological records in northern and central Italy, and (2) between lake-level highstands and glacier advances assumed to be driven by natural forcing before present-day global warming, support the hypothesis that changes in lake level shown in Figure 5 actually registered a climatic signal. In addition, correlations between lake-level records south and north of the Alps also suggest that over the last 4500 years northern and central Italy displayed a similar pattern of hydrological changes, with increasing humidity in response to Holocene cooling phases recognized in the North Atlantic area and to variations in solar activity (Bond *et al.*, 2001; Magny *et al.*, 2003; Blaauw *et al.*, 2004).

Furthermore, on a millennial scale and in agreement with the three lake-level records established at Fucino, Mezzano and Accesa (Figure 5), the Ledro record (Figure 3, upper panel) gives evidence of a similar general trend characterized by an increase in lake level during the late Holocene. However, it is possible that

Table 2 List for selected records of worldwide climate change at *c*. 3600–3300 cal. BP. The site numbers are those indicated in Figure 6

Site number	Site	References	Age (cal. yr BP)	Climatic signal
1	Lake Ledro, Trentino, Italy	This study	3450	wetter
2	Lake Accesa, Tuscany, Italy	Magny *et al.,* 2007a	3400	wetter
	Lago di Mezzano, Central Italy	Sadori *et al.,* 2004	3400	wetter
3	Adriatic Sea, Mediterranean	Piva *et al.,* 2008	3400	cooler and wetter
4	Rhone River delta, south France	Arnaud-Fassetta, 2004	3350	wetter
5	Loire River, central France	Wallinga, 2002	3200 ± 100	wetter
6	Jura and Pre-Alps (France), Swiss Plateau	Magny, 2004; Magny *et al.,* 2009	3450	cooler and wetter
7	Lake Holzmaar, Germany	Baier *et al.,* 2004	3660–3600	cooler
8	Germany	Zolitschka *et al.,* 2003	3500–3400	cooler and wetter
9	southern Germany	Billamboz, 2003	3530–3470	cooler
10	Kauner valley, Austria	Nicolussi *et al.,* 2005	3400	cooler
11	Alps, Austria	Schmidt *et al.,* 2007	3250	wetter
12	Swiss Plateau and Alps	Haas *et al.,* 1998	3600	cooler and wetter
13	Poland rivers	Gregory *et al.,* 2006	3500	wetter
14	Aegean Sea	Rohling *et al.,* 2002	3500	cooler
15	Spain rivers	Gregory *et al.,* 2006	3500	wetter
16	Lake Igelsjön, south Sweden	Hammarlund *et al.,* 2003	3500	wetter
17	south Norway	Shakesby *et al.,* 2007	3650	cooler
18	Lake Laihalampi, Finland	Heikkilä and Seppä, 2003	3500	cooler
19	Scandinavia, tree line	Berglund, 2003	3700–3600	cooler
20	Kola Peninsula, Russia	Boettger *et al.,* 2003	3500	cooler
21	Norwegian Sea	Calvo *et al.,* 2002	3500	cooler
22	Norwegian Sea	Birks and Koç, 2002	3500	cooler
23	Lake Vankavad, Russia	Sarmaja-Korjonen *et al.,* 2003	3620	wetter
24	Lake Sihailongwan, northeastern China	Schettler *et al.,* 2006	3600	drier
25	East Asia	Porter and Weijian, 2007	3290	colder and drier
26	Mount Everest, Himalaya glaciers	Finkel *et al.,* 2003	3600	cooler
27	Gujarat, India	Prasad *et al.,* 2007	3400	drier
28	Lake Masoko, Tanzania	Vincens *et al.,* 2003	3450	drier
29	Cold Air Cave, south Africa	Lee-Thorp *et al.,* 2001	3500	colder and drier
30	Australia	Haberle and David, 2004	3500	drier
31	EPICA, Antarctica	Masson-Delmotte *et al.,* 2004	3500	colder
32	Signy Island, maritime Antarctica	Noon *et al.,* 2003	3500	cooler and drier
33	Southern Andes, Argentina	Wenzens, 1999	3600	cooler
34	Patagonia	Glasser *et al.,* 2004	3600	cooler
35	Gulf of California	Pérez-Cruz, 2006	3360	cooler
36	Hemlock, British Columbia	Hallett *et al.,* 2003	3500	cooler and wetter
37	Vancouver Island	Patterson *et al.,* 2005	3400	wetter
38	Skinny Lake, British Columbia	Spooner *et al.,* 2002	3500	cooler
39	Southern Alaska	Barclay *et al.,* 2006	3500	cooler
40	White Lake	Li *et al.,* 2007	3350	drier
41	Boothia Peninsula, Canada	Zabenskie and Gayewski, 2007	3600	cooler
42	West Greenland	Lloyd *et al.,* 2007	3500	cooler
43	GISP2 Na+	Mayewski *et al.,* 1997	3500	deeper Iceland Low
44	GISP2 K+	Meeker and Mayewski, 2002	3500	Stronger Siberian High
45	North Iceland	Kirkbride *et al.,* 2006	3500	wetter
46	North Icelandic shelf	Jiang *et al.,* 2002	3600	cooler
47	Temple Hill moss, Scotland	Langdon *et al.,* 2003	3400	wetter
48	Loch Sunart, Scotland	Mokeddem *et al.,* 2007	3500	cooler
49	Britain, rivers	Macklin and Lewin, 2002	3550	wetter
50	Walton moss, England	Hughes *et al.,* 2000	3500	wetter
51	Azores, North Atlantic	Björck *et al.,* 2006	3400–3300	cooler and drier
52	North Atlantic ocean	Bond *et al.,* 2001	3500	cooler
53	North Atlantic ocean	Hall *et al.,* 2004	3600	cooler

forest clearance (as illustrated by pollen data in Figure 2 for Lake Ledro) could have amplified the response of water-tables to wetter climatic conditions by increasing runoff and consecutive colluvial accumulation around the lake outlets, particularly since the Bronze Age. Using palaeolimnological data, Filippi *et al*. (2007b) also hypothesized that, at Lake Nero (Trentino) located at an elevation of 2233 m a.s.l., relatively low lake-level conditions prevailed during the first part of the Holocene (up to *c.* 8000 cal. BP). Sediment hiatuses recognised by Lona (1970) from the pollen stratigraphy of mires in northern Italy provide additional support to the above observations. It is also noteworthy that a continuous sedimentation on the site of Ledro I initiated only after *c.* 2700 cal. BP, ie, during a time of a major climate reversal at the sub-Boreal–sub-Atlantic transition (van Geel *et al*., 1996).

Regarding the question of continuity of Middle Bronze Age lake- and wetland-dwellings (3600–3300 cal. BP) and their flourishing development north of the River Po, or the expansion of Terramare in the southern areas of the Po plain between 3550 and 3100 cal BP, one observes that these phenomena contrast with the general abandonment of the lake shores observed north of the Alps at the same time (see Figure 7). The lake-level record established at Ledro in northern Italy, like those reconstructed for Lakes

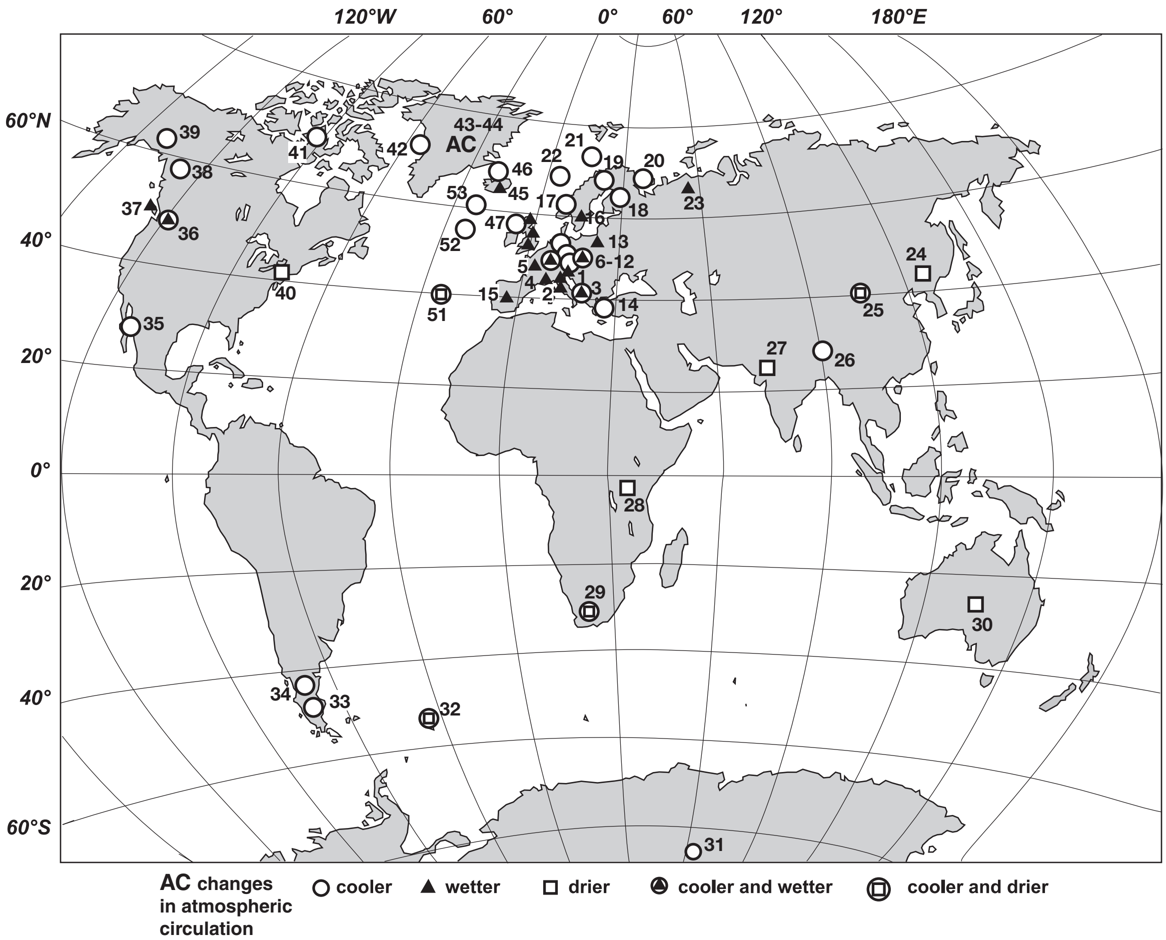

Figure 6 Widespread climate change at *c*. 3600–3300 cal. BP as reflected by multiproxy records listed in Table 2

Fucino, Mezzano and Accesa in central Italy (Figure 5), suggests that the singularity of the Italian humid settlements during the Middle and Recent Bronze Ages did not result from a peculiar climatic history: the transition from phases 13 to 12 at Ledro II dated to *c.* 3400 cal. BP coincides with a rise in lake level well marked by the cessation of peat formation (sediment unit 7) and its overlying by carbonate deposits (sediment unit 6). Furthermore, the climate reversal dated to *c.* 3600–3400 cal. BP and marked by higher lake-level conditions in northern and central Italy, as well north of the Alps, appears to correspond to a worldwide event observed in both hemispheres as illustrated by data listed in Table 2 and presented in Figure 6. Its synchronicity with a peak in the residual atmospheric ^{14}C content (Stuiver *et al*., 1998) and in the Greenland ^{10}Be record (Bond *et al*., 2001) suggests that it was associated with a decrease in solar activity. As shown by Figure 6, this climate reversal corresponds at mid-European latitudes to temperature cooling and increasing humidity resulting in higher lake levels, increasing river discharge, as well as glacier advances and tree limit decline in the Alpine area. Quantitative estimates of seasonal changes in west-central Europe show increasing annual precipitation by *c.* 70–100 mm (more particularly during the summer season) and decreasing mean annual temperature by *c.* 0.7°C (Magny *et al*., 2009).

Regarding the Bronze Age settlements of Lake Ledro, the Ledro II pollen diagram (Figure 2) suggests a relative decrease in the human impact at the transition between sediment units 7 and 6, ie, at *c.* 3400 cal. BP. However, the two pollen records obtained by Beug (1964) from the same site, although with a lower temporal resolution, invite caution before concluding too hastily concerning a possible influence of climate on Bronze Age settlements. First, Beug's data clearly show that the period of strong human impact began earlier than the deposition of peaty sediment unit 7. Second, they give evidence that the maximum of human impact on the vegetation cover does not coincide with the top of sediment unit 7, but with the basal part of carbonate sediment unit 6, ie, during a period of higher lake-level conditions. This indicates that the development of Bronze Age lake-dwellings cannot be explained only by climatic determinism. Further palaeoenvironmental and palaeoclimatic investigations, particularly in the outlet area where the most extensive archaeological site has been found, and additional core studies from the profundal zone of Lake Ledro, are still needed to obtain a more precise picture of possible past interactions between environment, climate and human settlement around Lake Ledro.

More generally speaking, on a regional scale, northern Italy was characterized by flourishing and lasting lake-dwelling settlements throughout the Bronze Age from *c.* 4050 to *c.* 3150/3050 cal. BP (Martinelli, 1996; Guidi and Bellintani, 1996; De Marinis *et al*., 2005). Maximal frequency of Bronze Age lake-dwellings spans the period 3550–3300/3250 cal. BP (Figure 7). In addition, on the Po plain, the development of Terramare covers the period 3550–3100 cal. BP with a maximum at *c.* 3400–3350 cal. BP (Cremaschi *et al*., 2006). Regarding the chronology, the beginning of the climatic reversal reflected at Ledro II by the transition from sediment units 7 to 6, is radiocarbon dated to *c.* 3400 cal. BP. Owing to lack of radiocarbon dates from sediment unit 6, it is not possible to establish the end of this high lake-level phase at Ledro. However, lithological changes observed in a sediment sequence at Lake Lucone, southwest of Lake Garda (Figure 5), give evidence of a lake-level lowering at *c.* 3050 cal. BP (Valsecchi *et al*., 2006).

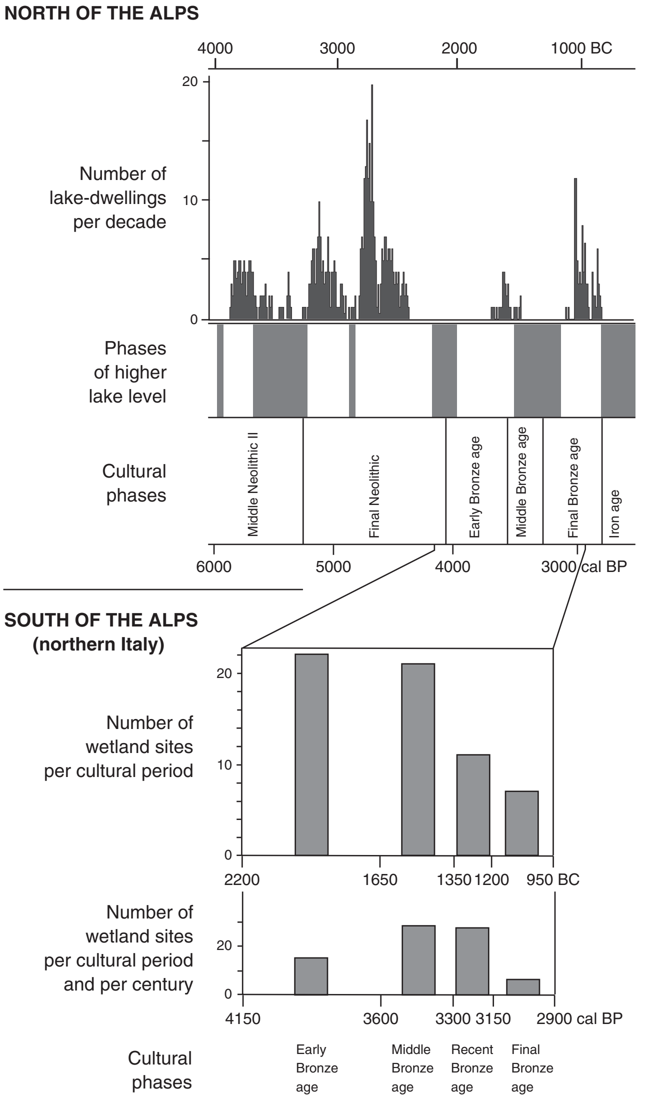

Figure 7 Frequency of lake-dwellings per cultural phases north and south of the Alps. Upper panel: Neolithic and Bronze age lake-dwellings in eastern France and on the Swiss Plateau (Magny, 2004). Lower panel: frequency of Bronze Age lake-dwellings in northern Italy as estimated from archaeological remains found in wetland areas (Guidi and Bellintani, 1996). Note that north of the Alps, a general abandonment of Bronze Age lake-dwellings during the climate reversal dated to *c*. 3500–3100 cal. BP is observed. This contrasts with the continuity and maximal frequency of wetland sites in northern Italy during the Middle and Recent Bronze Ages

This is in agreement with the age of climatic drying dated to *c*. 3100 cal. BP from geoarchaeological observations at the Terramare of Poviglio on the Po plain (Cremaschi *et al*., 2006). This regional northern Italy chronology also appears to be in agreement with that established at Lake Accesa in central Italy (Magny *et al*., 2007a), and to be close to that established north of the Alps in west-central Europe where the beginning of the climate reversal is tree-ring dated to 3460 cal. BP and its end to *c*. 3150–3100 cal. BP on the basis of tree-ring and radiocarbon dates (Magny *et al*., 2007b). Finally, the lake-level records from Ledro (this study) and Accesa (Magny *et al*., 2007a) as well as from west-central Europe (Magny, 2006; Magny *et al*., 2007b) show that, in fact, this phase of climate reversal was divided into distinct successive events (Figure 5).

Thus south of the Alps, despite a climate characterized by increasing moisture after 3400 cal. BP, Bronze Age settlements remained in humid areas of lake shores and in the Po plain, while drier climatic conditions prevailing after *c*. 3100 cal. BP appear to be synchronous with a general crisis of lake and wetland villages, and an abrupt end of Terramare. This flourishing of Bronze Age settlements in humid areas during a period marked by wetter climatic conditions probably suggests, as a working hypothesis, a peculiar socio-economic organization of Bronze Age societies in northern Italy. Alternatively, these Bronze Age societies may have collected more wild food plants from the surrounding woodland as shown from the palaeoethnobotanical material within the cultural layers of the Ledro settlement (Pinton and Carrara, 2007) or may have used additional food and fodder resources in case of losses or reduced crop yield as shown for the nearby Early to Mid-Bronze Age site of Fiavè-Carera for times of shortage (Karg, 1998; Haas *et al*., 1998a). In the specific case of Terramare, Cremaschi *et al*. (2006) have shown how their development was associated with original management of water to the fields through a network of irrigation ditches. Finally, far from a simplistic deterministic interpretation, the history of Bronze Age societies in northern Italy calls for a deeper knowledge of their social organization and subsistence strategy (control of resources, production of economic surplus in response to growing population) before a more comprehensive view of their possible interactions with environmental and climate conditions can be drawn.

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